YIELD AND BLAST ANALYSES WITH A UNIFIED THEORY OF EXPLOSIONS

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Summary

Yield is the most significant single number measured on any explosion because all effects --sympathetic reactions, fragments, blast damage-- derive from it. UTE offers the only adequate way to relate all explosions: non-ideal, any media, over all ranges in air, underwater, underground, confined spaces, heavy cases etc. The Form Factor and Lead Time are new extensions intended for safety analyses. A key idea in the form factor is to define average energy density in the blast wave relative to the peak value at the shock; it is the tacit assumption in scaling now. Lead Time means the difference in TOA between a sound signal and a shock wave; it scales, is a sensitive measure of yield and is nearly constant at long range. Applications include: absolute measure of prompt and delayed yields for blast, sympathetic reactions, fragments, propellant yield, surface effects, analysis with sparse data and simplified instrumentation.

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1. UTE Methods for New NESIP Problems

Yield means the blast or hydrodynamic energy released by any explosive and is the single most significant number to be measured in tests of any explosion.

All effects derive from yield and in principle can be predicted using it:

* Primary fragments: their sizes, shape, number, initial velocity of trajectory,
* Close-in blast, regarding both initial containment and secondary fragments,
* Low pressure damage, especially to specify the range where 1 psi occurs,
* All sympathetic reactions -detonation, deflagration, burning, their degree- be it directly from blast or via fragment and thermal loads it produces.

In fact, the Maximun Credible Event (MCE) really means the overall yield.

The Unified Theory of Explosions (UTE)[1] was developed for just such needs. UTE offers the only general way to describe any explosion: nuclear, non-ideal HE, over all ranges in air, underwater, underground, confined spaces, heavy cases etc. UTE offers two dozen concepts as tools to treat dozens of real non-ideal effects, nearly all being unknown or ignored in idealized classic theory and hydrocodes. A key idea in UTE is "prompt vs delayed" energy; it asserts that natural processes release some energy instantly, some more slowly, reinforcing blast farther out; much is trapped behind the negative phase too late ever to support the shock front. This separation is manifest by phenomena like afterburning, secondary shocks, and the most dramatic feature of any explosion: The fireball <u>is</u> delayed energy.

The NESIP Technology Base[2] itself rests on the Unified Theory of Explosions and much success in NESIP tests is due to versatile and accurate analyses with UTE.

Current NESIP problems now raise new and more specific questions about yield. For sympathetic reactions and in the design of inhibitors to prevent them:

* How much energy is released in a partial or in a low-order detonation?
* What are the actual prompt and delayed fractions in afterburning explosives?
* How to live with the large scatter of pressures measured in the real world?
* How to live with the narrow range of feasible, affordable measurements?
* What are the absolute energies involved in various modes of energy release?

For hazards involving propellants:

* What are the yields of a propellant on an absolute basis, detonated alone?
* If set off by an explosive warhead, how much does the propellant add to the prompt or delayed yield of the main explosion? Any new hazards?

To meet these new needs for NESIP, two major advances have been developed for UTE:

* A "form factor" method for bookkeeping the energy within a blast wave, to describe variable rates of afterburning, notably in heavily aluminized HE.
* A "lead-time" method, a simple reliable way to get yield from time-of-arrival.

They have widespread application to many explosion problems for NESIP and others. The purpose of this paper is to describe these new methods briefly, show the code and to test them by comparisons with a broad spectrum of field measurements.

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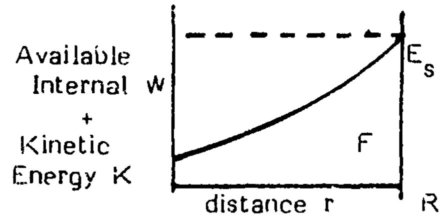
1. All references are listed at the end of the text, before Appendix A.

2. Form Factor Concept and Method

The form factor F is defined to mean the average hydrodynamic energy W+K in the wave relative to their peak sum E_s at the shock front. It is the ratio of the area shown here as F to the "square wave" as if E were constant at E_s.



If we define the yield Y(R) at any shock radius R as the integrated sum

$$Y(R) = 4pi \int_0^R (W + K) r^2 dr$$

normalize the integral, multiplying/dividing by the peak overpressure P_s-P_o, and by the mean value of any factor (like the available fraction A of energy at P)

$$Y(R) = \frac{4pi}{3} R^3 (P_s - P_o) A \int_0^1 \left[\frac{W + K}{P_s - P_o}\right] \frac{3}{A} \left[\left(\frac{r}{R}\right)^2 \frac{dr}{R}\right]$$

Thus F becomes the dimensionless fraction specified by the definite integral. Rigorously, we can just simply define a form factor F such that

yield		volume	O'pressure	mean A	form factor
Y(R)	=	(4pi/3) R^3	P	A	F

This definition for F is deceptively simple but is a powerful hydrodynamic tool. Many man-years and $millions were spent since World War II on elaborate hydrocodes, mostly to calculate pressure-distance curves with highly over-simplified models. Yet, both A and F are readily prescribed by the overpressure ratio (P_s/P_o-1); so we can always obtain the shock radius R at any pressure P simply from

$$R^3 = \frac{Y(R)}{(4pi/3)\,PAF}$$ P =overpressure, units consistent with Y and R

To calculate R, the code decreases Y(R) from its initial value Y_o by decrements

$$dY = \underbrace{-4pi\, Q\, R^2 dR}_{\text{losses}} + \underbrace{\text{Afterburning}}_{\text{gains}}$$

This can be done in bold steps, decreasing the pressure about 25% at each step. The same steps are used also for integrating the time of arrival of the shock wave.

A and F always appear together and here is an exact way to calculate AF. For exposition, let Q here mean the net loss (waste heat) and gain (afterburning). Then the ratio of the dissipation equation (dY=) to the definition for F (Y=):

$$\frac{dY}{Y} = \frac{-4pi\; Q\; R^2 dR}{(4pi/3) R^3 PAF} = -\frac{3(Q/P)\,dR}{AF \quad R}$$

gives

$$\frac{dY/Y}{dR/R} = \frac{3Q/P}{AF} \qquad \text{and } AF = \frac{3Q/P}{d\ln Y/d\ln R}$$

The machine code uses the local value of dln Y/dln R from each previous step, because dln Y/dln R varies slowly, from about -.5 at high pressure to -1 at low. Thus AF is bounded between 6Q/P at high pressures and 3Q/P at low pressure. Figure 1 shows these bounds and the transition region for the function AF vs P.

Analysis shows that AF goes like A(shock)/3 at high pressure, like $AP^2/3$ at low, and a suitable approximation, to a few percent in Y, without use of dln Y/dln R, and with a single parameter 1/3 for both high pressures and low, is:

$$AF \cong \frac{A(shock)}{3(1 + P_o/P)^2}$$

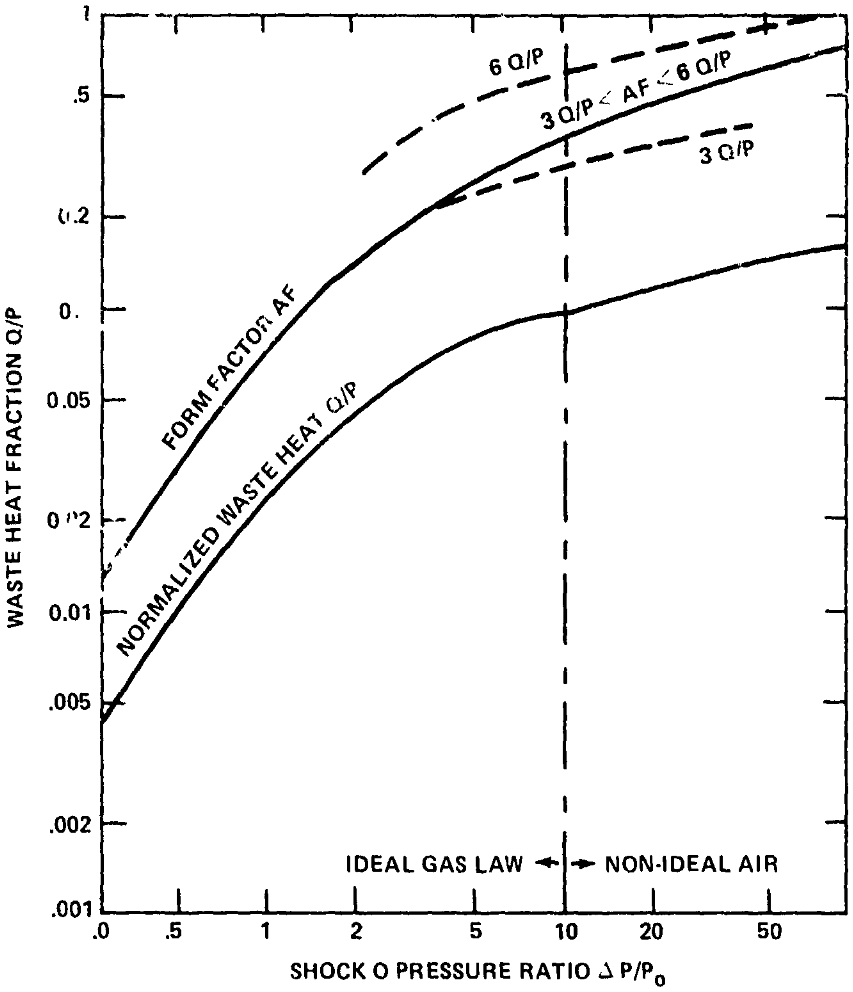


FIGURE 1. WASTE HEAT FRACTION AND FORM FACTOR VS. OVERPRESSURE

3. Lead-Time Concept and Method

Lead-time is a time-of-arrival method for measuring yield. With it we seek:

* An over-all measure of the shock history, sensitive to its early behavior.
* A way to circumvent uncertainty in yield from scatter in pressure measurements.
* Simpler instrumentation than the sophistication needed for good pressure data.

Time-of-arrival is an excellent measure for high pressure supersonic blast[3, 4, 5]; but at low pressure, TOA becomes sonic and an insensitive measure of shock strength. On the other hand, time-of-arrival can be measured with exceedingly high accuracy. Let us then measure the difference in time between the shock and a sound signal and define, at any range R:

$$\text{Lead-time} = \text{sound arrival} - \text{shock arrival time}$$
$$LT \qquad R/C_0 \quad - \quad T$$

This quantity ought to and does scale, is a sensitive measure at low pressures. Best of all, it becomes insensitive to the range at acoustic strength, so that one does not need an accurate gauge location --if the sound arrival is also measured.

As shown in Figure 2a, the early shock is highly supersonic: $U >> C_0$. There

$$R = \int U dt \quad \text{or} \quad T = \int dR/U \qquad \text{are both sensitive measures of yield.}$$

If we plot ln R vs. ln T as in Figure 2b, sound speed is a straight line, slope 1. But the shock time-of-arrival approaches it, partly because of the logarithmic plot. Also, the lead-time ceases to grow as the "overvelocity" vanishes at low pressure. As shown in Figure 2c, the lead-time approaches a scalable constant at long range.

In machine calulations, time-of-arrival adds up, using the same steps as for Y(R)·

$$TOA \;=\; dR/U \qquad U = \text{local shock velocity}$$

Because of the finite step size, an average value for 1/U is used; thus

$$\text{"dT"} = T_{i+1} - T_i = [1/U_{i+1} + 1/U_i]*[R_{i+1} - R_i]/2$$

The time-of-arrival and the lead-time are scaled just as for distance scaling. When the shock is strong, it is convenient, and a more independent measure to scale

$$\text{Relative yield} = (\text{Measured TOA/reference TOA})^3.$$

When the shock is weak (below the transition pressure) we scale lead-times as

$$\text{Relative yield} = (\text{measured LT/reference LT})^3.$$

Figures 3 and 4 illustrate practical reasons for developing the lead-time method. Large scatter in field pressure measurements is no doubt real, probably intrinsic, because a pressure gauge "feels" only the pressure at its surface, regardless of how rapidly pressure may vary in a boundary layer next to that surface[6, 7]. Figure 3 shows how pressure suffers from real variations both in space and in time Spacewise, the dust-laden boundary layer, brush, rough terrain all deplete yield. Timewise, the shock jets, and "rings" as it goes, in patterns that shift with time. The time-of-arrival will more nearly follow the grand-scale average growth of the hemisphere in free air above the ground surface, as idealized in Figure 4. While some lag may occur due to drag in the boundary layer, the corresponding error in lead-time is not nearly as severe as the pressure reduction from the same layer. Field measurements will test whether this expectation of less scatter is realized.

We also expect the lead-time will better "remember" the early history of the wave. If the explosion starts at low speed, is then sustained by afterburning, the TOA could be longer, the lead-time less, than by an instantaneous explosion. On the other hand, compensation occurs: the energetic shock wastes more energy early and after running a long time more slowly, may arrive later than the afterburner. UTE form factor calculations will show which is the stronger effect and how much.

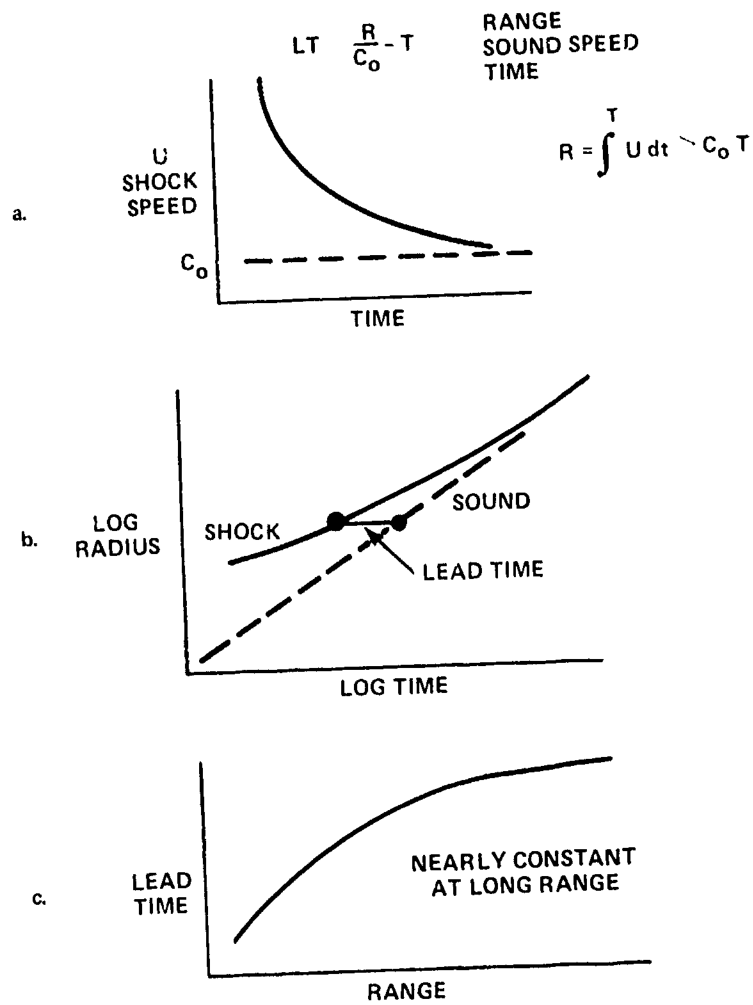


FIGURE 2. LEAD TIME METHOD

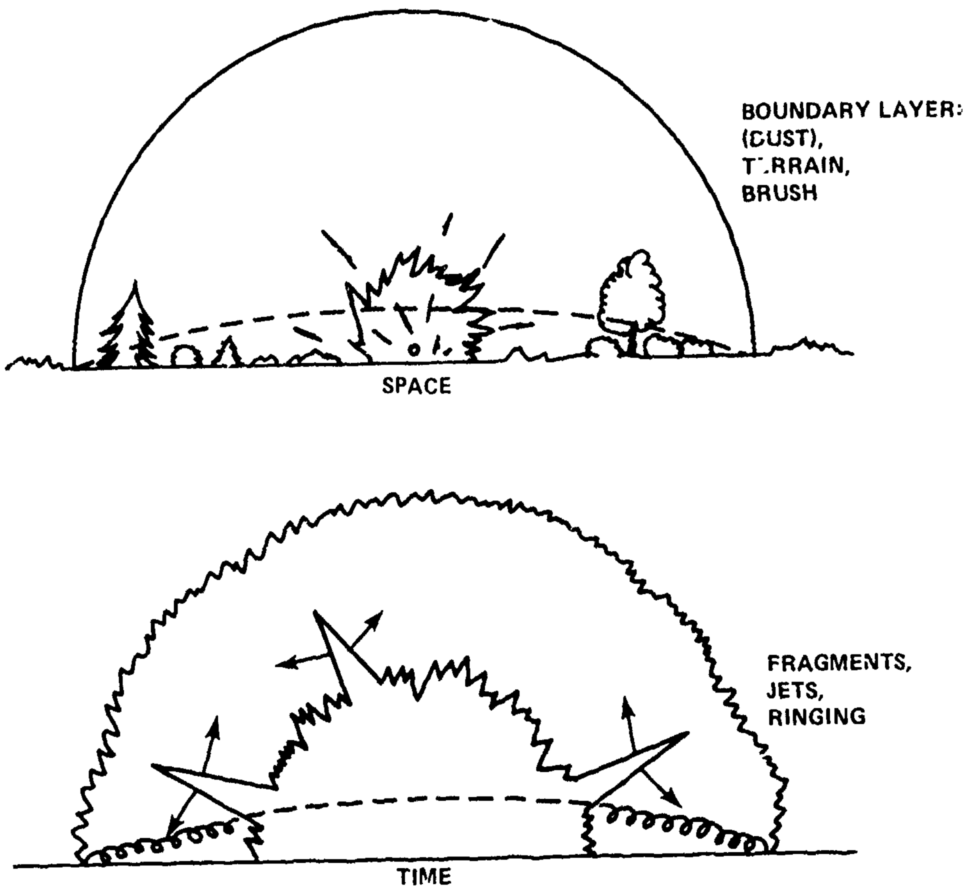


FIGURE 3. LOCAL PRESSURE VARIATIONS IN SPACE AND TIME

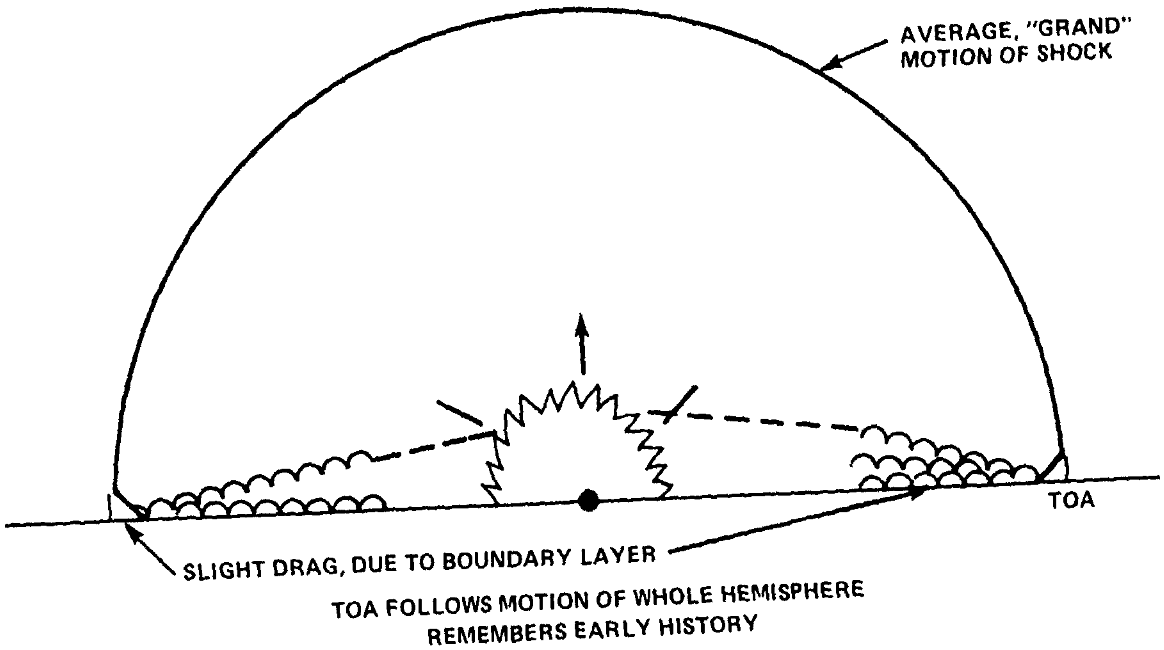


FIGURE 4. PERTURBATIONS ON TIME OF ARRIVAL

4. Machine Code and Printout

Appendix A lists the complete code, is well-annotated and may be self-explanatory. Written in advanced BASIC for a personal computer, it uses two-digit variables, compound statements in lines etc., but in principle could be copied and run as is.

Input parameters appear at the top of the printout (Tables 1, 2). They include:
Trial yield Y_0, here in joules; 4.188 10^{12} joules = 1 KT, 4.188 10^6 = 1 KG,
Mass M of explosive and immediate case, their specific energy H relative to air,
Initial radius R0: HE charge, isothermal sphere (nuclear), isobaric sphere (gas),
Ambient conditions: pressure P_0, sound speed C_0, and/or density D_0,
Afterburning fraction AB of Y_0: Transition pressure P_t, strong to weak shock.
If any above are missing, the code usually supplies a default value or computes one.
Input measurements for evaluation of yield include pressure P, range X, and/or TOA.

Major Options are included regarding input parameters, input data, and print-out.
Input any 3 of 4: yield Y0, initial pressure PI, mass M or specific energy H.
If any are omitted (usually P_i is unknown), the code will calculate it.
If all are given, the code will recompute H to make it consistent with the rest.
If P, X or T data are omitted; the code prints predictions anyway.
Time may be input either as discrete data or by a fitted curve. (So could distance).
Print-outs can be predictions only, + diagnostics, or yield analyses with graphs.

Major Computation Blocks (15 in all) are set off by remarks in the LIST.
Of interest as a guide to the code, they are listed on the first page of Appendix A.

Computation Procedure. After the predictions for conditions at the charge radius:

1. Select a new pressure; next data or reducing the previous P by $10^{-.1}$ = 1/1.26.
2. Compute waste heat G, afterburning increment YA, available energy fraction A, form factor w/A as AF, shock velocity U; all are functions of the pressure.
3. Compute yield decrement Y1, afterburning YA, new yield $Y = Y_i - Y1 + YA$, then iterate for "mass-corrected" radius $Z = (R^3 + H*M)^{1/3}$, then get R from Z.
4. Calculate TOA from dT = dR/U, and new TOA = old TOA + dT.
5. Calculate relative yield from range, essentially as (measured/calculated)$^{\text{cubed}}$
6. Calculate relative yield from TOA or lead-time, as (measured/calculated)$^{\text{cubed}}$.
7. Summarize with an average yield relative to input yield, for range and/or TOA including the standard deviation of the measured yields about their mean.

Table 1 illustrates a printout of close-in predictions of a massless explosion: M=0. The initial pressure PI and radius R0 mark the end of a nuclear radiative phase. The isothermal sphere implies a "square wave", i.e. larger form factor than normal, nor can the interior gas be accelerated instantly to reproduce a normal blast wave. The code allows it to do so gradually by computing an "inertial mass" as shown. The point is: In a gaseous explosion, spark gap, or any other non-ideal blast wave, a like initial dissimilarity occurs and will be so accommodated with all UTE codes. We note that the inertial mass found, 544 kg ≅ mass of air engulfed at that radius.

Table 2 illustrates another printout option that graphs the relative yield from TOA. It compares predicted lead-times for a Mk 48 torpedo with the field test data. Initial yield included a ground reflection factor 1.5 and afterburning of PBXN 103. The ambient conditions are for the test site at Socorro, NM, altitude ≅ 5200 feet. The input mass was 1038 pounds, essentially the warhead, most of which is PBXN-103. This was the very first test of the code. The relative yield is plotted as T (time). The TOA yield, .90 predicted, means lead-time itself is within $.9^{1/3}$=.965, 3.5%. Also shown, not plotted, are the pressure results: relative yield 1.099, 3.2% in R.

TABLE 1

RUN

UNIFIED THEORY OF EXPLOSIONS (UTE), FORM FACTOR METHOD AND TIMES
NUCLEAR COMPOSITE DATA, NOLTR 72-209

Total Yield = 4.18879E+12 Input mass = 0 Input H = .25
Ambient pressure = 100000 Ambient density = 1.16271
Ambient sound speed = 347 Inertial mass = 544.037
Afterburning fraction = 0 Complete at Pt/Po = 1.99526

O'PRESSURE	RADIUS	YIELD	ARRIVAL TIME	LEAD TIME
79432.9	4.21063	.839084	9.50147E-06	.0121249
63095.8	4.51563	.818802	1.31606E-05	.0130002
50118.7	4.83647	.798519	1.74959E-05	.0139205
39810.7	5.17656	.778182	2.26698E-05	.0148954
31622.7	5.60958	.75347	3.00725E-05	.0161359
25118.8	6.06141	.728707	3.8739E-05	.0174293
19952.5	6.53499	.703973	4.89312E-05	.0187839
15848.9	7.03314	.679343	6.09603E-05	.0202075
13600	7.37917	.663073	7.01477E-05	.0211955
12589.3	7.55862	.654897	7.51919E-05	.0217076
10000	8.11427	.630716	9.20832E-05	.023292
7943.29	8.70291	.60686	1.12161E-04	.0249683
6309.56	9.32753	.583393	1.36065E-04	.0267445
5011.86	9.99126	.560374	1.64565E-04	.0286287
3981.06	10.6957	.537912	1.98504E-04	.0306249
3750	10.8641	.532836	2.07216E-04	.0311015
3162.28	11.3621	.518595	2.34559E-04	.0325092
2511.89	12.079	.499882	2.78187E-04	.0345317
1995.26	12.8509	.481772	3.30994E-04	.0367034
1584.89	13.6825	.464255	3.9494E-04	.0390359

TABLE 2

RUN

UNIFIED THEORY OF EXPLOSIONS (UTE), FORM FACTOR METHOD AND TIMES
INHIBITOR TESTS ON MK48 TORPEDOES, JUNE 1982, PRELIMINARY DATA SHOT #1

Total Yield = 3.85452E+09 Input mass = 471.252 Input H = .5
Ambient pressure = 83000 Ambient density = .991783
Ambient sound speed = 342.29 Calculated Initial Pressure = 1.08279E+07
Afterburning fraction = .3 Complete at Pt/Po = 1.99526

```
P/P0       TOA Yield Meas. T    .6       Relative TOA Yield          1.4
 .456874   .884941   .0679804 .              T                        .
 .376298   .762048   .0809575 .        T                              .
 .223453   .938644   .128332  .                 T                     .
 .201855   .88243    .140158  .              T                        .
 .154507   .983428   .176062  .                    T                  .
 .0930362  .933178   .268408  .                 T                     .
 .0880522  .915598   .280596  .                 T                     .
```

Yield, relative to input = 1.09959
Standard deviation, % = 21.1099 based on 7 samples, P=> 1 psi
TOA Yield, relative to input = .900038
Standard deviation, TOA yield, % = 7.77284 based on 7 samples

5. Test of Methods with Nuclear and HE Data

The form factor and lead-time methods were tested against a broad spectrum of data. Nuclear data check on absolute yields by their radiochemical and hydrodynamic yields and check the equation of state more severely at higher pressures than HE reaches. HE data check non-ideal effects like large mass, afterburning, and secondary shocks. The broad range of data checks for self-consistency and exposes systematic errors. Figures 6 to 10 graph the detailed results and Table 3 summarizes them.

Blast theory is usually checked against data by pressure-distance plots like Fig. 5. But as seen there, UTE matches composite data so closely that graphs are inadequate. Instead, UTE computes the relative yield at each pressure level and we plot that. On Figure 5, the line widths approach 3% in radius, 10% in yield, too small to see. On Figures 6 to 10, the three central lines are relative yields of 1.0 $\pm$ 10%, as if the graph of Fig 5 were blown up to broaden the lines to the band width shown.

1 KT Nuclear Composite[1, 7] (Fig 6) covers from 13600 to .07 bars, 10^5 times. The average yield 1.024 KT $\pm$ 5.3% matches the line width of the source curve[7] and is significant because the high pressures are superbly accurate fireball data.[3] The TOA yields also are excellent at high pressures; overall is 1.08 KT $\pm$ 14%. The excursion at low pressures is probably due to a fitted time-of-arrival curve. The consistency in yield is assurance that the high pressure UTE equation of state is realistic relative to the ideal gas law, used for air at pressures below 10 bars.

KING Fireball[3] (Fig 7) is probably the best pressure-distance data in existence: high yield, air drop, negligible mass effect, all-fission, a perfect circle fireball. Radiochemistry gave 545 KT, hydrodynamic yield 555 KT, fireball scaling 595 KT. Here, pressure and TOA both give 586 KT; scatter of 3-7% is round-off error in data. This one test is definitve: all the measured data are digital --no graphing errors.

Nuclear Blast Standard[8] (Fig 8) is not data but an artifical viscosity hydrocode. The absolute value of yield .997 KT checks superbly, but the scatter is over 14%. Its initial pressures are known to be 50% low from actual fireball theory and data. At low pressure its P-R curve decays like $R^{-1.1}$, flatter than UTE, $P \sim R^{-1.33}$. Classic theory predicts R^{-1}, but field measurements always decay much faster.

1 KG TNT Composite[9] (Fig 9): splendid agreement/consistency, up to the charge, and for $.07 < P/P_0 < 2$, the UTE calculation agrees well with often-measured $P \sim R^{-1.4}$. The excursion below .07 bars is probably not real, but old data piously fit to R^{-1}. The absolute yield is .714 KG, 714 cal/gm; earlier UTE methnds gave 720 cal/gm.

1KG H6 Composite[9] (Fig 10_) is a check with a heavily aluiminized explosive, where the afterburning fraction is estimated as .30. The consistency 5% is suberb. The absolute yield is 1.014 KG HE, or 1014 cal/g, equivalent to 1.4 times TNT.

Previous UTE, DSC[1] (not shown) has been used successfully on so many NESIP and other tests that it is of interest to use a DSC calculation (M=0) as input data here. The result: Relative yield 1.00000, $\pm$ 3.5%, no sensible difference between them.

TABLE 3

TESTS OF {FORM FACTOR / LEAD-TIME} – METHODS

VERSUS	NOMINAL	SPAN, BARS	YIELD	% CONSISTENCY
NUCLEAR COMPOSITE (FITTED TOA)	1 KT	13,600 → .07	RANGE 1.029 KT TOA (1.087)	± 5.3 (14.8)
KING FIREBALL	555-595 KT	1,900 → 46	RANGE 586 KT TOA 586 KT	± 3.6 ± 6.8
AIR FORCE 1 KT STANDARD	1 KT	10,000 → .07	RANGE .997 KT	± 14.6
TNT COMPOSITE	1 KG	47 → .07	RANGE .714 KG	± 8.6
H-6 COMPOSITE	1 KG	8.3 → .16	RANGE 1.02 KG	± 5.1
UTE DSC CONSTANT "q"	1	13,600 → .07	1.00005	± 3.6

INDIVIDUAL POINTS

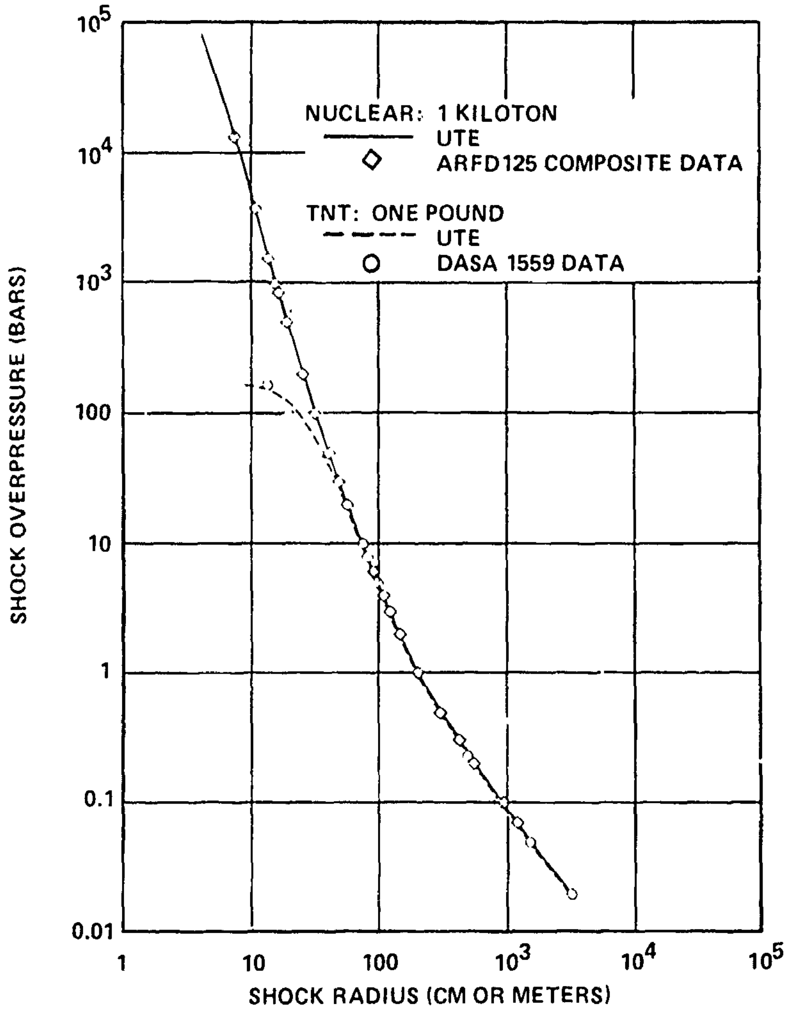


FIGURE 5. COMPARISON OF UTE PREDICTIONS WITH NUCLEAR AND TNT DATA

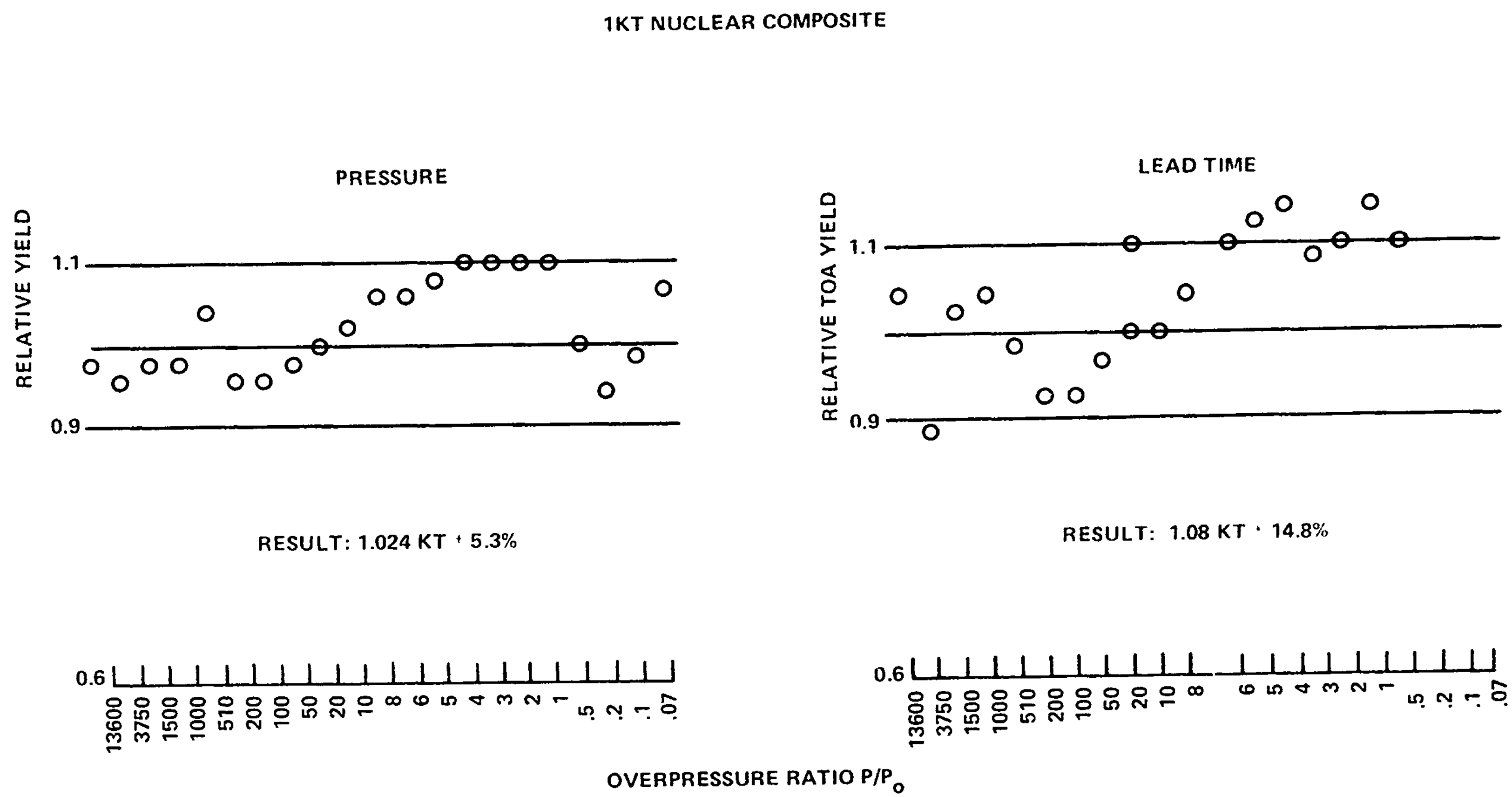


FIGURE 6. RELATIVE YIELD VS OVERPRESSURE, 1 KT NUCLEAR COMPOSITE

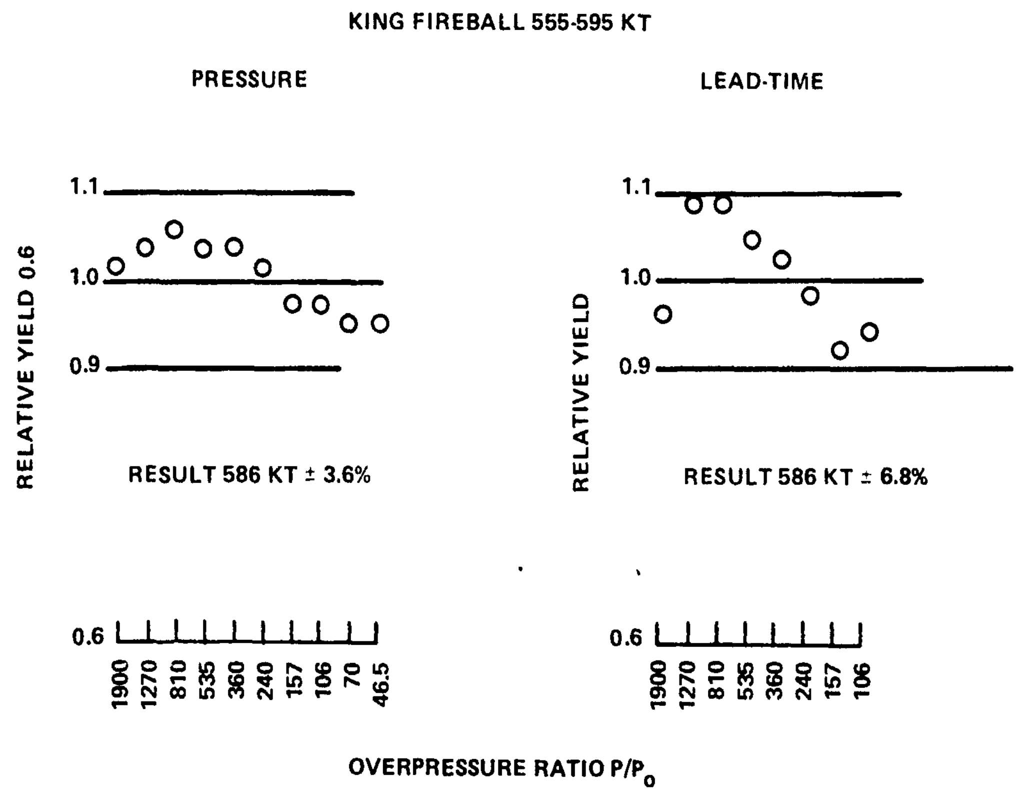


FIGURE 7. RELATIVE YIELD VS OVERPRESSURE, KING

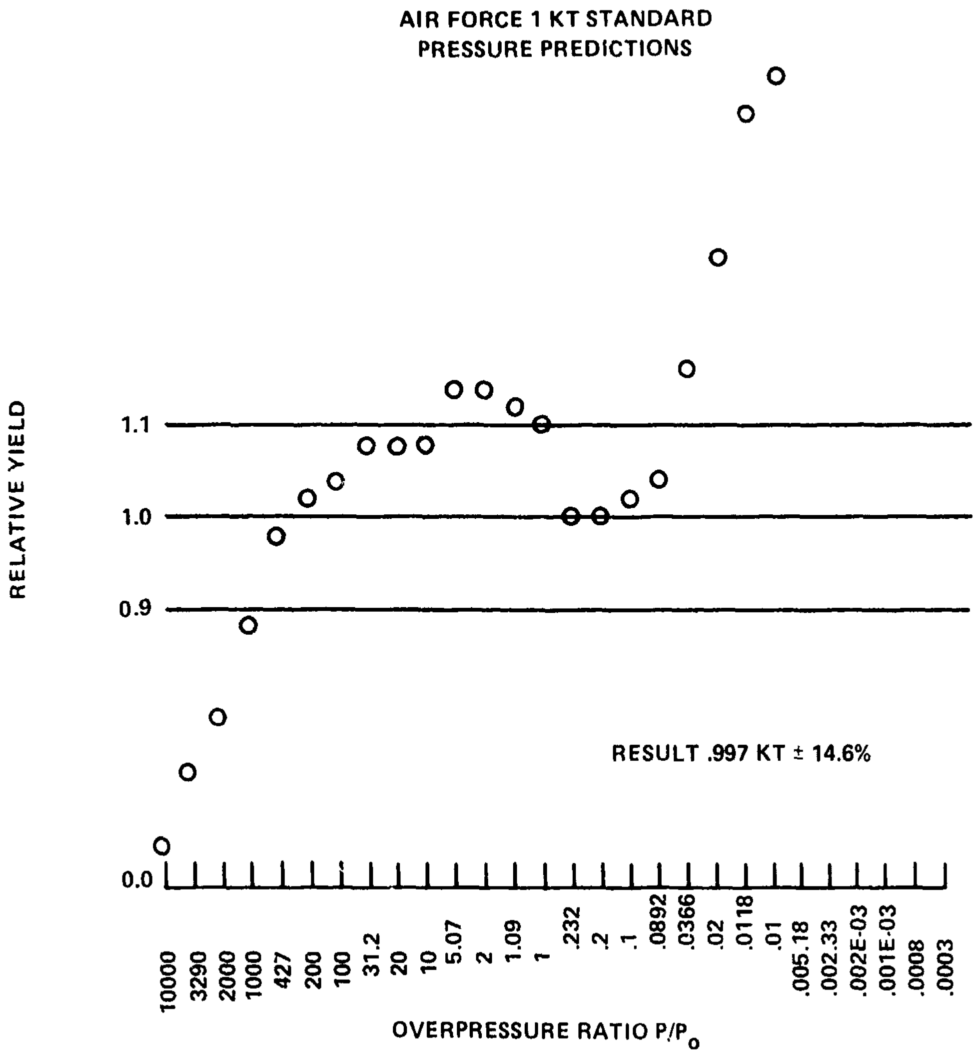


FIGURE 8. RELATIVE YIELD VS OVERPRESSURE, AF 1KT

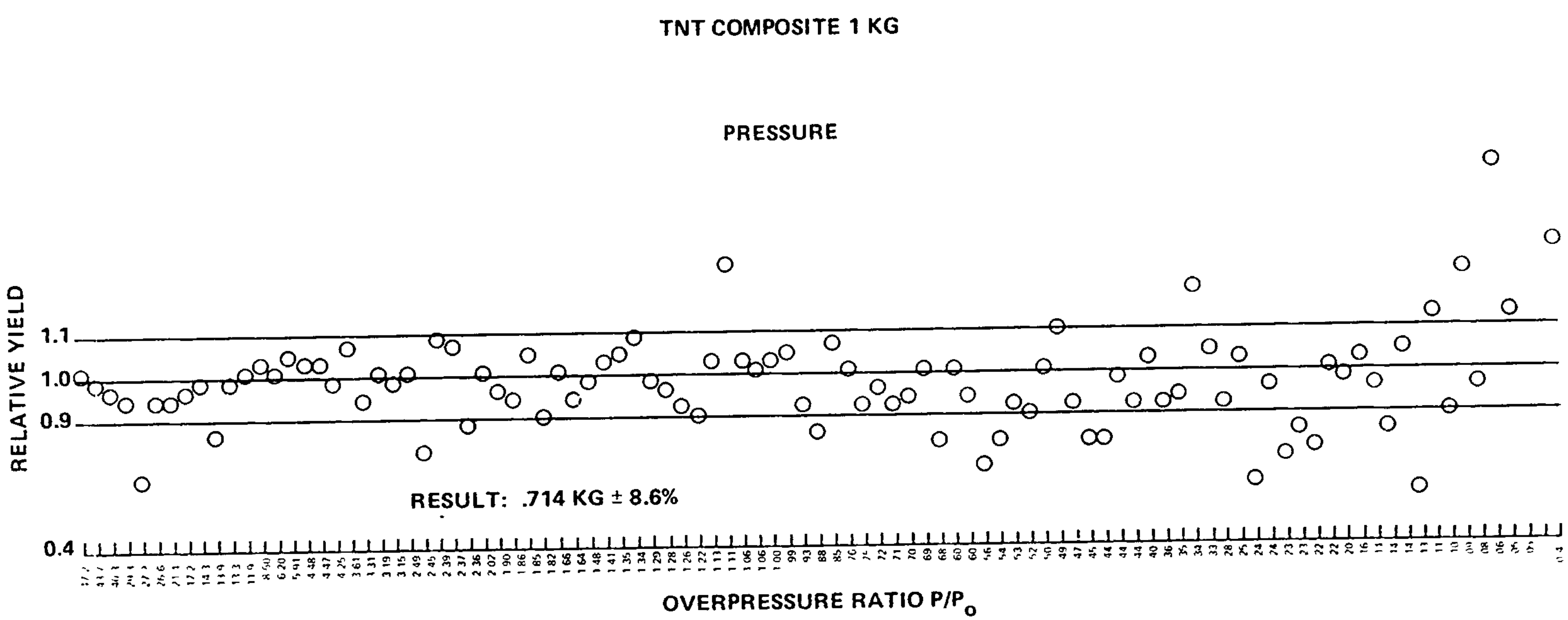


FIGURE 9. RELATIVE YIELD VS OVERPRESSURE, TNT COMPOSITE

H-6 COMPOSITE, 1 KILOGRAM
PRESSURE MEASUREMENTS

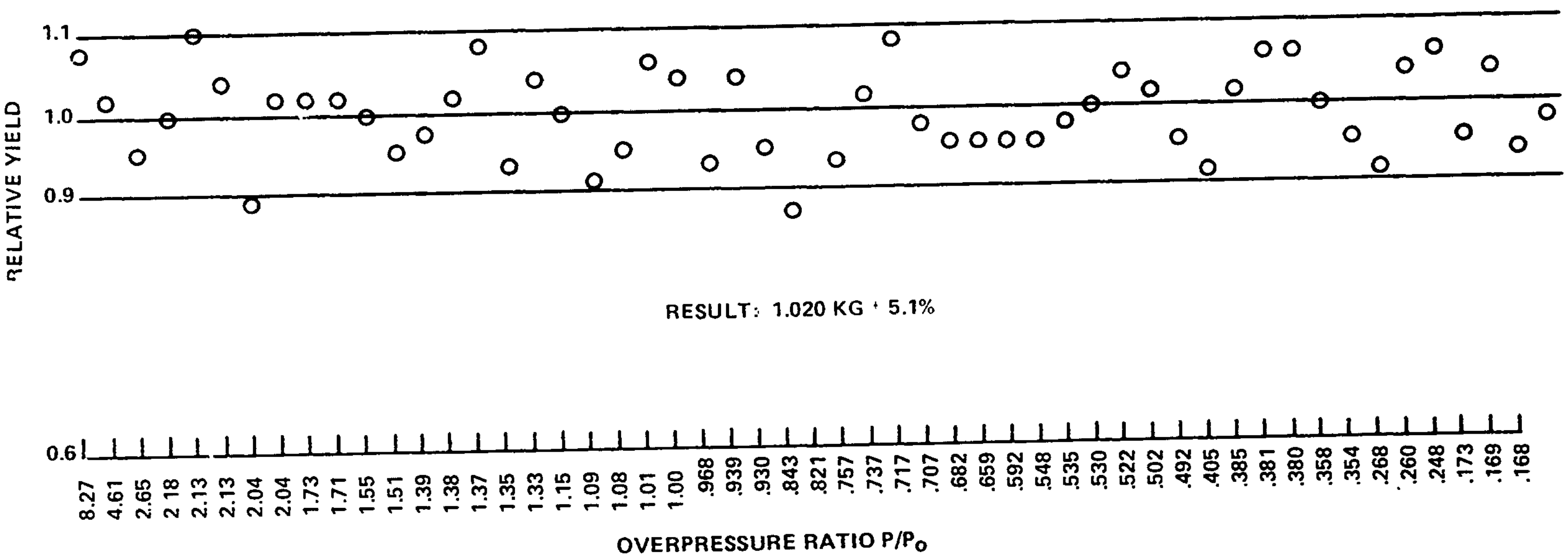


FIGURE 10. RELATIVE YIELD VS OVERPRESSURE, H-6

6. MK. 48 Torpedo Inhibitor Tests

Recent field experiments on the design of inhibitors[2, 10] for the Mk 48 torpedo provide an opportunity to test/apply these new methods to a typical NESIP problem. The test set-up is shown at the top of Table 4; essentially, it was a donor warhead flanked by two acceptor warheads, with inhibitor plates between them, on each side. On one side the plates were steel, on the other side aluminum, thicknesses as shown. Detonation was suitably instrumented with witness plates, cameras and flash panels and in a blast line by pairs of pressure-time gages near 140, 240, 300, 400 feet. Even so, critical questions arise in all such tests:

If the witness plate did hole, did full detonation of the entire warhead occur?

If it did not hole, could the charge have moved and a delayed detonation occur?

To understand either case, we need to measure the yield output for each event.

The test results were unequivocal and corroborative among all the test evidence. Shots 1 and 2: no acceptor detonated. Shot 3: the aluminum side holed in situ. The 140 and 240 foot gages on Shot #3 had double pulses that coalesced by 300 feet. Still the critical questions remain: How much energy did each shot yield?

Peak pressure results are compared on Figure 11 with the pre-shot calculations. The data on #1 seem somewhat low, on #2 somewhat high. But scatter makes it doubtful: Excepting two "low" points on #1, one "high" on #2, 13 remaining points replicate. Shot #3 leaves no doubt the curve beyond 300 feet represents twice the yield.

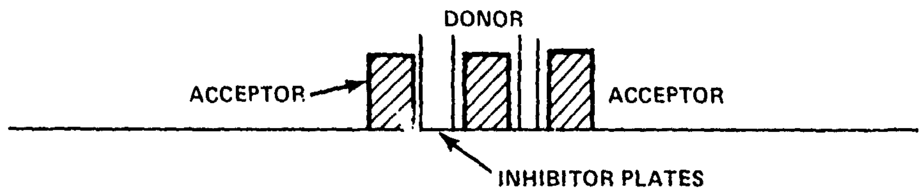
The corresponding pre-shot estimates and lead-time data are shown on figure 12. Now there is no doubt that Shot #2 was larger than #1, nor that Shot #3 was double. Considering this was the first test of a lead-time prediction on HE, it checks well.

Relative yields on shots 1 and 2 are plotted on Figures 13-14, summarized on Table 4.
Compare the pressure results: 1012 KG $\pm$ 21.1% vs. 1386 KG $\pm$ 17.9%.
The ratio 1386/1012 = 1.37 is impressive, except that 37% is not far different from the arithmetic or the Pythagorean sum of deviations, 21.1+17.9. One is just not sure.
Now compare lead-time yields: 828 KG $\pm$ 7.8% vs. 1108 KG $\pm$ 6.8%.
Again: 1108/828 = 1.34 is impressive and 34 is more than twice any sum of 7.6 and 6.8
These confidence levels make a strong, objective case for the merits of lead-time.

As Table 4 indicates, the yields on shot 3 were definitely doubled, by either method. but no predictions had been made with history effects for catch-up of second pulses.

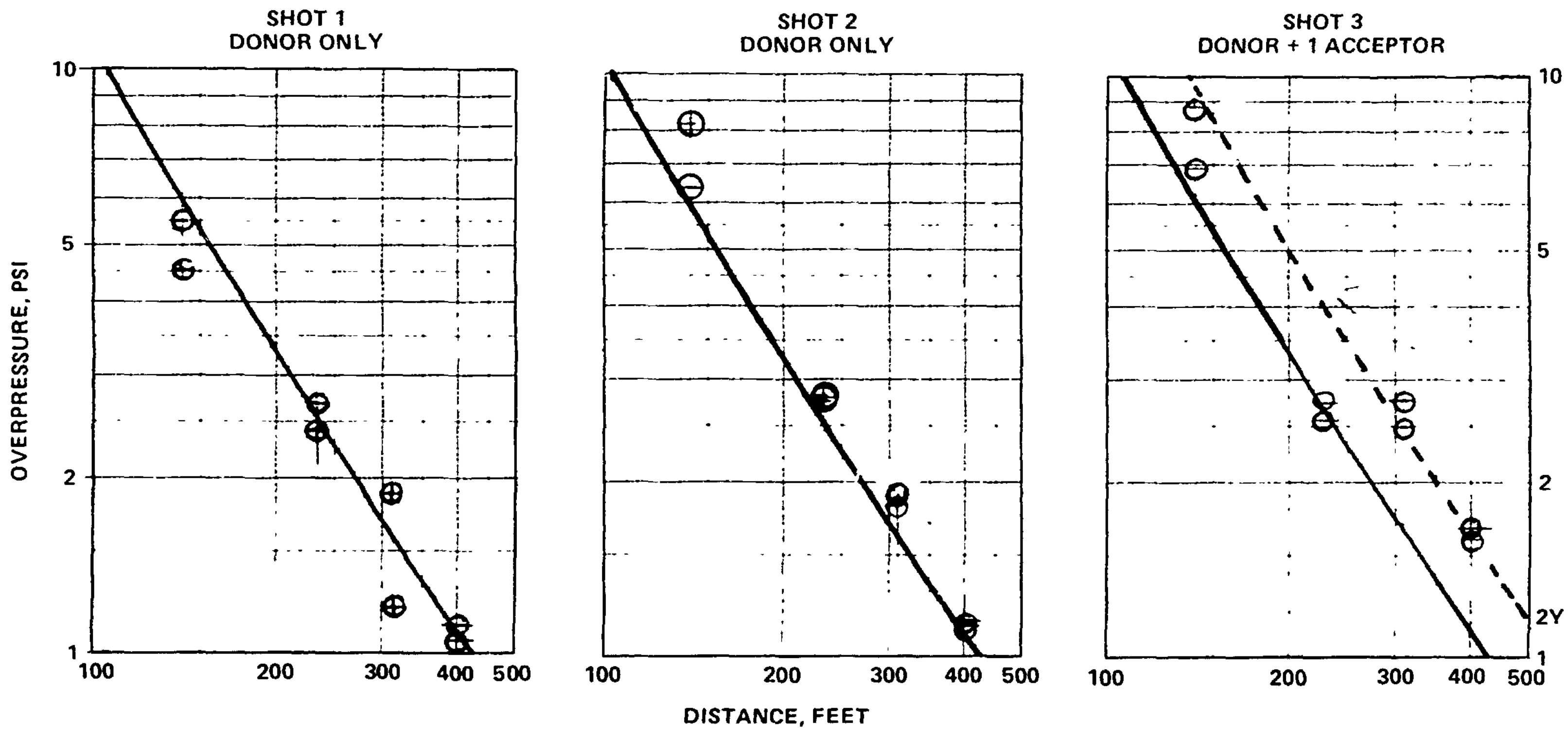
We have yet to resolve why the lead-time gives lower yields on both shots 1 and 2. Compare range/lead-time: 1012/828 = 1.23 (shot 1) and 1306/1108= 1.25 (shot 2). It is precarious to prognosticate with preliminary data until they really do firm up, but two main ideas are noteworthy here: 1. measuring sound velocity, 2. reflection . Among many ways to measure sound velocity --absolute temperature + wind velocity, a microcharge fired just before the main shock, or compute C_o from the P-t data-- all three differed at the field tests, and we have not yet resolved why.
On the other hand, the lead-time could well be telling us a real fact:
The calculations assumed the torpedo explosion reflected instantly off the ground.
Whereas we know it must have run for some time as a free air explosion,
and was slowed by the inhibitor plates and by the acceptor in that direction.
We also know that the shock is slowed by the dust-load in the boundary layer
The present results are based on sound velocity as calculated from pressure gages.

TABLE 4.
MK 48 TORPEDO INHIBITOR TESTS



	NOMINAL	SPAN, PSI	YIELD (REFLE 1.)	CONSISTENCY
SHOT #1 1 1/2" ALUMINUM	1000 KG	10 → 1	RANGE: 1012 KG TOA: 828 KG	± 21.1% ± 7.8%
#2 3/4" ALUMINUM	1000 KG	10 → 1	RANGE: 1386 KG TOA: 1108 KG	± 17.9% ± 6.8%
#3 3/8" ALUMINUM	1000 KG	10 → 1	DOUBLED. DOUBLED:	

PRELIMINARY DATA AND ANALYSES



(Preliminary Data)
FIGURE 11. MK 48 TORPEDO INHIBITOR TESTS

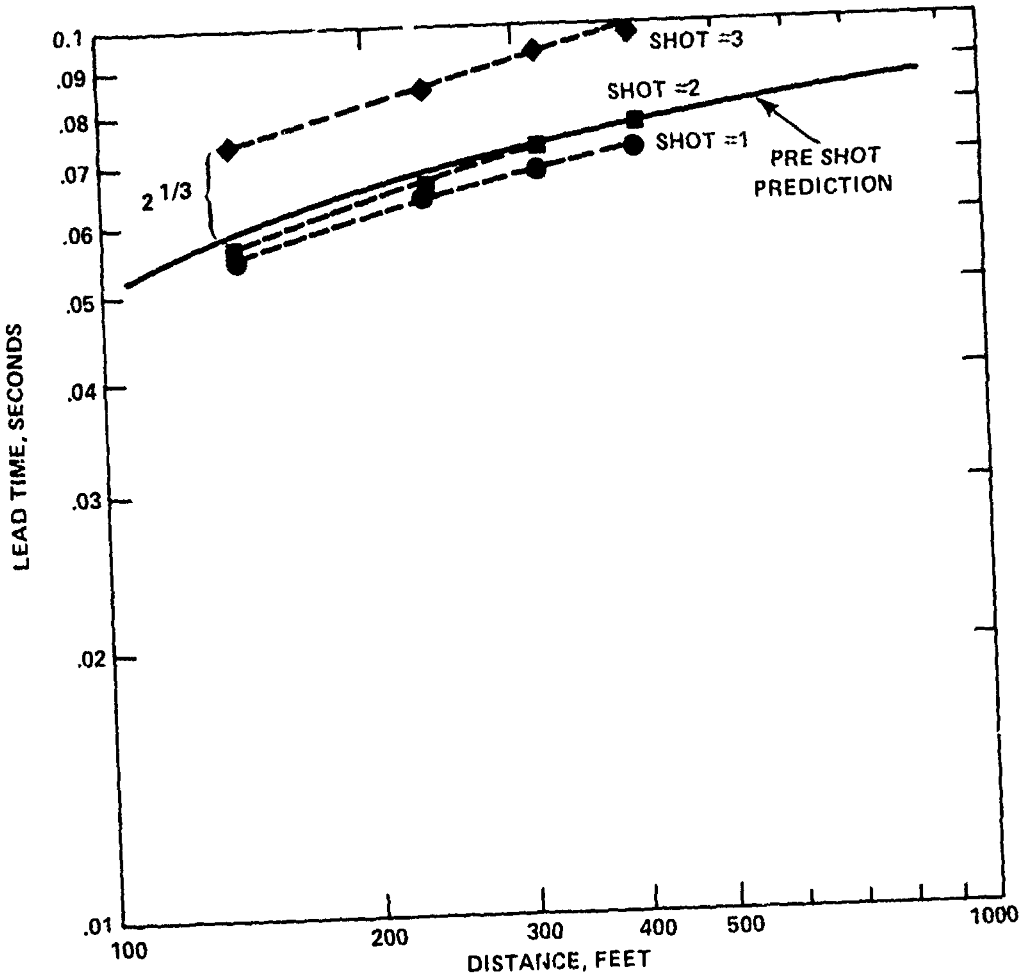


FIGURE 12. TEST OF LEAD TIME OF MK 48 TESTS

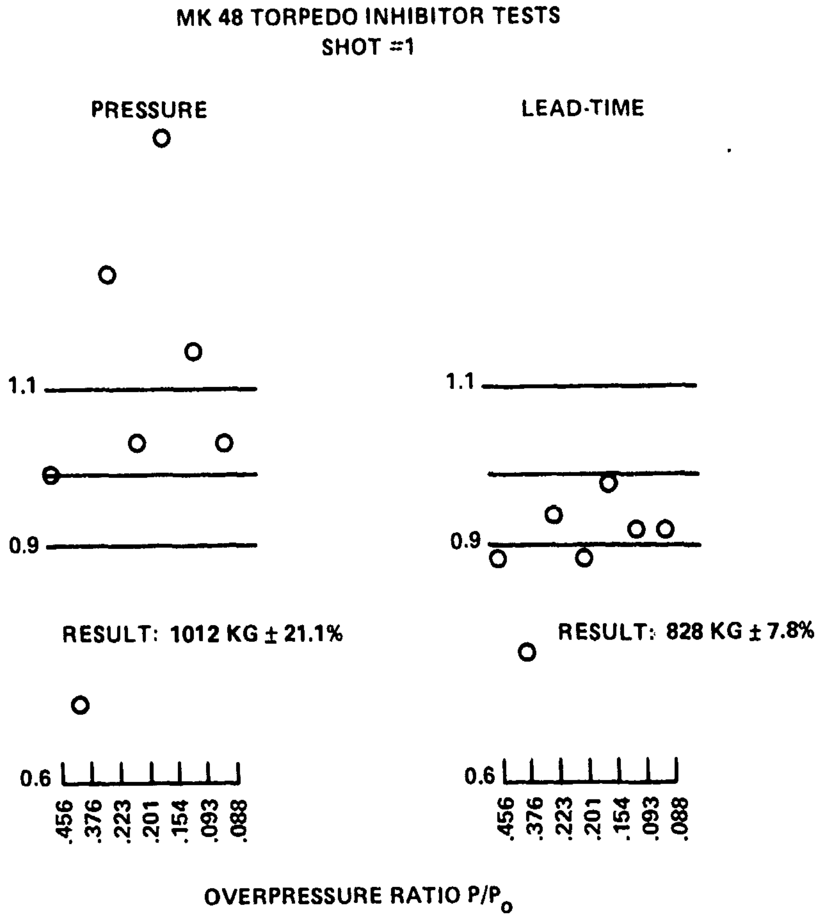


FIGURE 13. RELATIVE YIELD VS OVERPRESSURE, SHOT 1

MK 48 TORPEDO INHIBITOR TESTS
SHOT #2

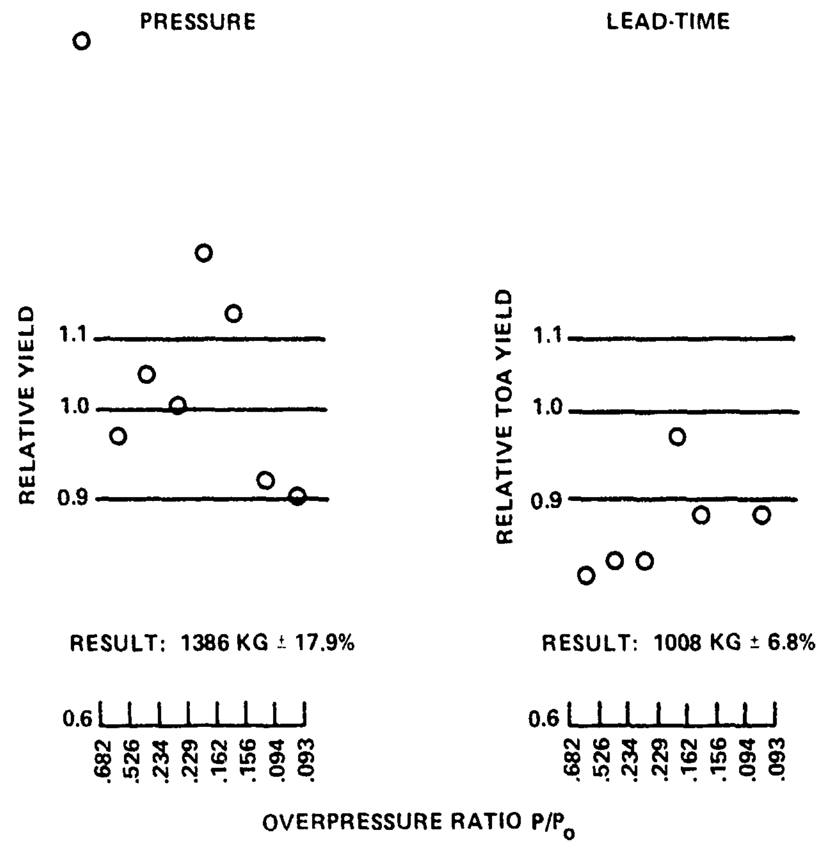


FIGURE 14. RELATIVE YIELD VS OVERPRESSURE, SHOT 2

7. Conclusions

1. Form Factor. The form factor method with the unified theory of explosions (UTE) agrees well with nuclear and high explosive data, with earlier methods of UTE and offers a facile way to describe non-ideal and non-spherical explosions.

2. Lead-Time. The lead-time method is a simply instrumented way to measure yield at high and low shock strengths, with much less scatter than pressure measurements.

3. UTEFORM. Form factor and lead-time together offer a new powerful diagnostic tool to solve the unpredictably broad problems which explosion safety requires such as sympathetic reactions, early blast history, unusual afterburning or energy release.

4. Absolute Yield. The definition 10^{12} cal/KT = 10^{6} cal/KG = 10^{3} cal/gm is a modern rational way to correlate any explosion: nuclear, chemical, other source.
It is necessary because:
Different HE's do not necessarily scale with each other nor with other sources.
That is, equivalent weight is certainly not constant at high shock strengths and is not necessarily constant even at acoustic shock strengths.

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8. "Nuclear Blast Standard (1KT)" Needham, C. Havens, M.,Knauth, C. AFWL 73-55 (Rev), Air Force Weapons Laboratory, April, 1975.
9. Michael Swisdak, NSWC, private communication.
10. "Module to prevent sympathetic detonation in munitions" F.B. Porzel, U.S. Patent 4,286,708.

Appendix A

LIST for UTEFORM

Form Factor and Lead-Time Methods With the Unified Theory of Explosions

Major Computation Blocks by Line Numbers:

0-199 Input parameters
200-299 Compute PI. given Y0 and H
299-300 Compute M or H, given Y0, PI and either M or H
400-450 Compute trial Y, if unspecified
450-500 Print column headings
500-570 Data processing and pressure selection
570-699 Energy gains, losses, new yield and range
700-800 Equation of state sub-routine
800-850 Energy gain and loss sub-routines
850-899 Form factor sub-routines
900-999 Time-of-Arrival sub-rountine
1000-1400 Input data: pressure, distance, time
1400-1500 Example: Fitted time-of-arrival sub-routine for a nuclear composite.
1500-1599 Relative yields from range and time-of-arrival
1600-2000 Yield, standard deviations and termination.

Hints:

1. Any consistent set of units may be used.
   If energy is in joules, R in meters, M in kg, then P is in pascals $=10^{-5}$ bars.
   Line 50, as written, converts from KT (4 pi/3 $*10^{12}$) to joules;
   use line 51 to enter the KT, KG or cal/gm.
2. Change data with a line editor, it will save retyping the remarks in that line.
3. In general, the variables are defined by remarks the first time used in the LIST.
4. For help. call Fran Porzel, 202 394 1166 (office) or 703 533 7973 (home).

```
0 J  =2                     '0 = Predictions, 1= analysis, 2,3 = range or TOA yield
1 REM..Any self consistent units may be used; P is in pascals for Y kg, R meters
5  PRINT "NUCOMP/UT8", DATE$, TIME$:IF J=0 THEN 15
15  PRINT "UNIFIED THEORY OF EXPLOSIONS (UTE), FORM FACTOR METHOD AND TIMES"
23  PRINT "NUCLEAR COMPOSITE DATA, NOLTR 72-209"
25 B = 4*3.141592/3       'Form factor for sphere; mech. eq of heat,  13.6 deg cal.
30 P0 = 1E5               'Ambient pressure; 1 bar = 1E5 pascals =1E5 kg/m/sec^2
31 P0 = 1*P0              'Erases possible previous entry
35 E0 = 2.5 : K0 = 1/E0 +1           'energy and adiabatic coefficients, ambient
40 D0 =1.1613 :C0 = 1138.45*.3048   'input ambient density D0 or sound speed C0 or both
41 D0 = 1.11613           'Erases possible previous entry for Do
43  IF C0 > 0 THEN D0 = K0*P0/C0^2 : GOTO 50    'Override D0 by equation of state
46    IF C0 = 0 THEN C0 = SQR(K0*P0/D0)
50 Y0 = B*10^12           'Yield; 1 KT = 10^12 cal = 4pi/3*1e12 kg m^2/m^3/sec^2
51 Y0 =Y0*1.0             'Relative yields from earlier runs or fits
52                        '        1 KG = 10^6 cal = 4pi/3*1e6 kg m^2/m^3/sec^2
53  AB=.00                'Afterburning fraction
56 Y0 = Y0*(1-AB)         'Yield before afterburning
60 R0 =4.2                'Radius of isothermal sphere or charge radius , 1 KT
61 R0 = 1*R0              'Erases possible previous entry
70 H = .25                'specific energy of debris to air; use .5 for massive
80 M =0
83       M = H*M0/B/D0   'converts mass to equivalent volume of air
85 IF R0 = 0 THEN R0 = (M0/B/1500)^(1/3) ELSE 86 'Replace 1500 w/ D of charge
86       Z0 = (R0^3 + M)^(1/3) 'Z = Sshock radius corrected for UTE mass effect
90 PI = 8E9
93 PT = P0*10^.3          'Transition pressure, book-keep end of afterburning
95 QZ = 3.5: YZ = .5     'Default intial values for dlnQ/dlnZ, dlnY/dlnZ (ideal)
100  PRINT "Total Yield ="Y0/(1-AB), "Input mass ="M0, "Input H ="H
120 PRINT "Ambient pressure ="P0, "Ambient density ="D0
140 PRINT "Ambient sound speed ="C0,
199 REM...........OPTION TO CALCULATE PI, GIVEN Y0 AND H..................
200  P = PI :IF PI >0 THEN 300
210 PI = Y0/B/Z0^3       'Trial value;  A*F approx 1 for strong shocks
220 P = PI
230 GOSUB 700
240 AF = A/3
250 Y = Y0*(1-Q/P)        'Estimate for waste heat of charge or isothermal sphere
260 P = Y/B/AF/Z0^3
270 IF ABS(P/PI -1) <.001 THEN 285
280 PI = P: GOTO 230     'Iterate for PI
285 PC = PI               'Save revised pressure PC at charge surface
290 PRINT "Calculated Initial Pressure ="P
296 GOTO  445
299 REM.................OPTION TO CALCULATE H, GIVEN PI AND Y............
300 GOSUB 700
315 IF Y0 =0 THEN 400
320 Y = Y0*(1-Q/P)                  'Waste heat in radiative phase or chargew/af = 1
330 IF M0>0 AND H>0 THEN 390
340 Z0=(Y/B/PI/AF)^(1/3)
350 MH = B*D0*(Z0^3 -R0^3)
360 IF M0 = 0 THEN M0 = MH/H ELSE 380
370 PRINT "Inertial mass ="M0 : IF J = 0 THEN 380
380 IF H = 0 THEN H = MH/M0 ELSE 390
385 PRINT "Calculated specific energy H ="H
390 M = H*M0/B/D0           'Computes "inertial volume" from apparent mass
```

```
399 REM................OPTION TO CALCULATE Y (Needs debugging)
400 IF Y = 0 THEN Y = B*PI*A*F*Z0^3 ELSE 430
405 GOTO 930
410 Y0 = Y/(1- PI/P0)^(1/K -1))
420  PRINT "Calculated initial yield Y0 ="Y0
430 P = PI
445 PRINT"Afterburning fraction ="AB,          "Complete at Pt/Po ="PT/P0
450 IF J<2 THEN PRINT"O'PRESSURE", "RADIUS", "YIELD","ARRIVAL TIME","LEAD TIME"
470 IF J<2 THEN PRINT "     ", "Measured","Range Yield","Measured", "TOA Yield"
475 IF J = 1 THEN PRINT "    Q/P","   Z", "   YZ", "   QZ". "   AF"
480 IF J = 2 THEN PRINT "O'Press."TAB(10)"Rel. Yld"   TAB(20)"dlnY/dlnZ" TAB(30)".6",
490 IF J = 3 THEN PRINT "P/P0" TAB(10)"TOA Yield" TAB(20)"Meas. T" TAB(30)".6",
491 IF J = 2 OR 3 THEN PRINT "Relative Yield" TAB(69)"1.4"
499 REM................PRESSURE SELECTION...............................
500 READ PX,X : IF PX = 0 THEN 1600
510 PX= PX*1E5
513 REM   Use GOT_ 525 with no measured times or if TX is in seconds
515 GOSUB 1400          'Sub-routine for fiited TOA curve
520 TX = TX/1000        'Fitted curve was in milliseconds
525    IF P>PX THEN N = .1*INT(10*LOG(PI)/LOG(10) ) : GOTO 540
526    PI = PX :  H=0 : X0 =X : GOTO 300
530 N = N - 0.1
540 P = 10^N
545 IF ABS(PI/P -1)<.001 THEN 530
550 IF P <PX THEN P = PX
560 GOSUB 700
570 REM,........GAINS, LOSSFS, NEW YIELD AND ARNGE...................
580 IF QI = 0 THEN 630           'By-pass gain or loss at R0; avoid /0 error @600
590 YH = Y  +YA                  'Add afterburning; hold  Y as Z is iterated
595 IF QZ = 0 THEN 605  'IF Q = QI THEN Z =ZI and Y1 = 0
600  Y1 = 3*B*QI*(ZI^3)/(QZ -3)*(1 - (Q/QI)^(1-3/QZ))
605  IF P<PT THEN YA = 0         'No afterburning beyond transition pressure
610 Y = YH -Y1
630 Z =(Y/B/P/AF)^(1/3)
631 IF QI = 0 THEN 637
632 IF Q = QI OR Z = ZI THEN 635       'Circumvents repeateu pressure problem
633 QZ = LOG(QI/Q)/LOG(Z/ZI)
635 IF ABS(Z2/Z - 1)>.00001 THEN Z2 = Z : GOTO 595
637 IF M>Z^3 THEN Z = (M +R0^3)^(1/3)
640 R = (Z^3 - M)^(1/3)
645 ON ERROR GOTO   650          'Avoids d/0 on initial pass
646 YZ = LOG(YI/Y)/LOG(Z/ZI)    'Calculate dlnY/dlnZ for later use in 870
650 GOSUB 900.          'Get time increment
660 T = T +T1
675 IF J >1 THEN 687
680  PRINT P/P0, R, Y/Y0, T, R/C0 -T
687  IF ABS(P/PX-1)<.001  THFN GOSUB 1500
690 IF J = 1 THEN PRINT"  "Q/P, Z, "   "YZ, "   "QZ, "   "AF
696 PI=P : QI = Q : ZI =Z : RI =R :UI =US :YI = Y:AI=AF
698 IF ABS(P/PX -1)<.001 THEN 500 ELSE 530
Ready
>
```

```
699 REM................EQUATION OF STATE SUB-ROUTINE........................
700 P = P/P0            'Equation of state is described best by pressure ratio
710 IF P<10     THEN E=2.5 :GOTO 760    'E is ratio =energy/PV, i.e.epsilonh
720 IF P<100    THEN E= 2.5 + 1.5*LOG(P/10)/LOG(10)   :GOTO 760
730 IF P<700    THEN E= 4.0 + 1.55*LOG(P/100)/LOG(7)  :GOTO 760
740 IF P<1000   THEN E =5.55 -.55*LOG(P/700)/LOG(10/7) :GOTO 760
745 IF P<4000   THEN E =5.0 - LOG(P/1000)/LOG(4)       :GOTO 760
750 IF P<40000  THEN E = 4.0    :GOTO 760
755 IF P>40000  THEN E = 4.0 - .67*LOG(P/40000)/LOG(2) :GOTO 760
760 D = ((2*E +1)*(1 +P) +1)/(P + 2*E0 +2)      ' density ratio, real gas
770 A = E*(1 +P)/P*(1- (1+P)^(-1/(E +1))) 'Prompt energy factor A =Work/(P-P0)V
780 K = 1/E +1                          'Same as epsilon = 1/(k-1)
790 P = P*P0                            'get back to absolute overpressures
799 REM................ENERGY LOSS AND GAIN  SUBROUTINE......................
800 IF P/P0 < .06 THEN 840      'Q will soon truncate to 0 if you don't do this
805 IF P/P0 <11.3 THEN 830      'Exact match w/ ideal gas @ P=11.3, 3.4
810 L = .4342948*LOG(P/P0)       'convert pressure ratio to  log base 10
820 Q = P0*10^((21.75-L)*(L-1)/16) :GOTO 845  'Semi-empirical fit for real air
830 Q = P0*((1 +P/P0)^(1/K)/D -1)/(K-1) :GOTO 842      'classical adiabat
840 Q  =P0*(K+1)*((P/P0/K)^3)*(1 - 1.5*P/P0)/12        'acoustic dissipation
842  IF P>PT THEN 845           'Argument: wave form and losses are manifest at shock
843 Q = Q*(1 +AB)               'Argument: secondary shock, other losses
845 ZP= 1/4                     'dlnZ/dlnP; assunes YA goes as volume and tim
846 YA = AB*Y0*((PC/P)^ZP -(PC/PI)^ZP)/((PC/PT)^ZP - 1) 'AB is prop. to Z-zi
847 IF P<PT THEN YA = 0
850 REM................AF = A*F SUBROUTINE.......................
860 IF P>PT THEN  AF =A/3/(1 +P0/P)^2/(1 + AB) :GOTO 890
861 REM: Strong shock, F= .42, mean A=.8*A(shock), /(1 +AB) is peaked wave form
865 IF YZ = 0 THEN YZ = 1
870 IF P<PT THEN AF =3*Q/P/YZ          'Weak and second  shock, YZ stable
880 IF AF>AI OR AF<=0 THEN AF= AI      'By passes troubles at transition pressure
890 RETURN
900 REM .............TIME-OF ARRIVAL SUB-ROUTINE..........................
910 IF P/P0 >450 THEN K =1.2 +.2*LOG(P/P0/450)/LOG(2)  : GOTO 940  'real gas K
920 IF P/P0 >15 THEN K = 1.4 - .2*LOG(P/P0/15)/LOG(30): GOTO 940   'real gas K
930 K = K0
940 US = SQR(P/D0/(1 -1/D))             'used previous K to calculate U
945 IF ZI = 0 THEN UI = US              ' UI not yet initialized as in 696
950 UB = (1/US + 1/UI)/2                'Mean for integrating dt as dX/U
960 T1 = UB*(R -RI)                'Time increment
970 IF ZI = 0 AND P/P0 >10000 THEN T1 = .2*T1 : GOTO 990     'Radiative phase
980 IF ZI = 0 THEN T1 = .5*T1           'ball park estimate for detonations
990 RETURN
999 REM............INPUT MEASURED DATA. AND/OR LOWEST PRESSURE FOR CALCULAUION.
1000 DATA 13600, 7.32,   3750, 10.7,   1550, 13.7
1010 DATA  1000, 15.5,    510, 19.2,    200, 25.6
1020 DATA   100, 32.2,     50, 41,       20, 57.3
1030 DATA    10., 75.1,     8, 82.4,      6, 91.5
1040 DATA     5, 98.8,      4, 108.5,     3, 122.5
1050 DATA     2, 147.4,    1.0, 208,      .5, 302
1060 DATA    .2, 544,     .10, 905,     .07, 1200
```

```
1400 REM.............. SUB-ROUTINE FOR FITTED TIME OF ARRIVAL............
1410 IF (PX/P0) < 500 THEN 1430
1420 TX = (PX/P0/500)^(-4/5) : GOTO 1490
1430 TX = (PX/P0/500)^(-6/7)
1435 TX = TX*TX^(LOG(TX)/175
1440 IF ABS(T2/TX -1) < .00001 THEN 1490
1450 T2 = TX :GOTO 1430
1490  RETURN
1499 REM.................RANGE AND TIME OF ARRIVAL YIELD................
1500 IF ABS(P/PX -1)>.001  THEN 1595  'Passes only  measured points
1510 YX= (X^3 +M)/Z^3
1533 TB = INT(50*YX + .25)
1534 IF TB>77 THEN TB = 77
1535 IF J = 2 THEN PRINT P/P0 TAB(10)YX TAB(20)YZ  TAB(30)"."TAB(TB)"Y" TAB(70)"."
1545  IF US/C0 >2 THEN YT = (TX/T)^3 : GOTO 1555
1550 YT = ((X/C0 -TX)/(R/C0 -T))^3
1555 TT = INT(50*YT + .25)
1560 IF TB>77 THEN TB= 77
1570 IF J = 3 THEN PRINT P/P0 TAB(10)YT TAB(20)T TAB(30)"." TAB(TT)"T" TAB(70)"."
1575 IF P<.068*P0 THEN 1590
1576 I = I +1
1580 SX = SX +YX
1585 VX = VX + YX^2
1586 IT = IT +1
1587 ST = ST + YT
1588 VT = VT + YT^2
1590 IF J = 1 THEN PRINT"    Meas:", X, "*"YX, TX, "*"YT
1595 RETURN
1599 REM.................YIELDS AND STANDARD DEVIATIONS................
1600 IF I <2 THEN 2000
1602  S = VX/(I-1)- (SX^2)/I/(I-1)
1604 IF IT < 2 THEN 1610
1606 S2 = VT/(IT-1) -(ST^2)/IT/(IT-1)
1608 PRINT
1610 PRINT "Yield, relative to input =" SX/I
1630 PRINT "Standard deviation, % =" 100*SQR(S)*(I/SX) "based on" I "samples, P=> 1 psi"
1640 IF ST = 0 THEN 1680
1650 PRINT "TOA Yield, relative to input =" ST/IT
1670 PRINT "Standard deviation, TOA yield, % ="100*SQR(S2)*(IT/ST)"based on "IT"samples"
1990 DATA 0, 0, 0
2000 END
```